A STUDY OF UNDERWATER DIVER TACTILE SENSITIVITY

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THESIS

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ABSTRACT

This thesis examines the effects of underwater submersion and prolonged underwater submersion on a diver's tactile sensitivity. The method of constant stimulus is used to determine size discrimination thresholds. The stimuli used are squares of hard acrylic plastic into which holes of varying diameters have been drilled.

Four tests were administered to each subject. One test was administered on dry land in the open air and served as the standard. The other three tests were administered underwater at various time intervals.

The conclusion drawn from this research is that a diver's tactile sensitivity as measured by his ability to make size discriminations is not affected by underwater submersion or even prolonged underwater submersion of sixty-six minutes. Furthermore, the thresholds of approximately one millimeter, determined in this thesis, are consistent with the findings of past research in this field.

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I. INTRODUCTION

A. BASIS FOR RESEARCH

In the last twenty years, a large amount of research has been conducted in the field of tactile sensitivity. Most of this research has been directed by members of the medical profession seeking to better their understanding of somesthetic perception or by persons interested in developing better systems of communication through the sense of touch. The U. S. Navy has, through the years, pioneered research relating to underwater diver performance, but there has been little research which link together the fields of tactile discrimination and the underwater environment.

B. TOPIC AND ORIGIN

This thesis examines the effects of complete underwater submersion on diver tactile sensitivity. Underwater tests are performed and compared to dry (land) test results. The factor of the length of time submerged is also investigated. The topic of investigation for this thesis and the funding for it originated with the Navy Experimental Diving Unit, Washington Navy Yard, Washington, D. C.

II. BACKGROUND

A. REQUIREMENTS

In order to investigate underwater diver tactile sensitivity, a test is needed which could be performed both on land and underwater. The test must also be designed to yield numerical data which is capable of being geometrically and mathematically analyzed. The data, once analyzed, must show quantitatively the effect of an underwater environment on a diver's tactile sensitivity. Finally, the test must be one which measures accurately and reliably that which is recognized as the tactile sense.

B. PAST RESEARCH

1. The Two-Point Limen

The two-point limen test determines the ability of a subject to discriminate two simultaneously stimulated points as separate; it is generally considered the standard measure of spatio-tactile resolution (Vierck and Jones, 21). Jenkins (13) points out that the instructions given to the subjects taking this type of test are critical. The results obtained from telling the subjects to report two stimuli whenever they feel a departure from a single stimuli do not match results obtained when the subjects are instructed to report two only when they clearly feel two stimuli. Although the test with the latter set of instructions is

considered to test the true two-point limen, the threshold is still two to three times larger than the error of localization (Jenkins, 13).

Vierck and Jones seem justified in rejecting this test as a standard of spatio-tactile resolution. They state that the two-point limen test has seemingly evolved from thinking relevant to vision where it is important to separate objects; whereas, in tactile stimulation discrimination, it is more important to determine stimuli size, locus, quality, and intensity rather than to separate stimuli. In their experiments, Vierck and Jones used solid plastic cylinders of different diameters and determined that size discrimination thresholds were smaller by a factor of ten than the accepted two-point thresholds. From their studies, Vierck and Jones conclude that "the skin is primarily organized for localization and size discrimination" (21, p. 489).

2. <u>"V" Test and "C" Ring Test</u>

The "V" Test was introduced by Mackworth (16) in 1953 and consisted of two straight edges clamped together to form a shallow V. Subjects would then place the pad of an extended digit finger at different distances from the point of the V and state whether they felt a single solid object or two closely parallel objects. This test was also used in a study of the effects of cold on diver tactile sensitivity (Bowen, 3) prepared for the Office of Naval Research.

Dolly Chan (4) developed a "C" Ring Test for testing tactile acuity in 1964, using 5mm diameter metal rings, some complete (O-rings) and some slotted (C-rings). The slots in the rings varied between 1mm.

and 4mm. Subjects reported whether they felt "O" or "C" rings when the stimuli came in contact with the pad of an extended index finger. Both these tests essentially determine a two-point sensitivity threshold. Chan states that the "C" test makes use of a technique based on the "Landolt C-Test" developed to test visual acuity. This type of test is precisely what Vierck and Jones were referring to when they said that the two-point threshold tests apparently evolve from thinking relevant to vision.

3. Tests Involving Communication Type Stimuli

The largest amount of research involving tactual discrimination has been directed toward determining methods of communication for the blind or deaf and blind using the sense of touch. Bumps, raised lines and figures, vibrations, textures, and patterns have been investigated to determine what could be easily recognized by touch. Even patterns of minute air currents have been investigated, but all of these miriad of stimuli hinge primarily on the subject's ability to "learn" to discriminate differences in the stimuli and not on their tactual thresholds. Hence, these stimuli are not appropriate for measuring tactual acuity or tactual discrimination levels.

4. Abstract Shape and Other Tests

Gibson (8) investigated haptic perception of unfamiliar shapes. Because most ordinary objects proved too easy to identify, he sculptured free-form art objects with convex, concave, and saddle-shaped surfaces with six protuberances. Subjects were presented two objects and asked, after presentation of the second object, whether or not it was the same

or different from the first object. Gibson found that the subjects made fewer and fewer mistakes as they became more familiar with the objects; hence, a continuing learning effect until errorless judgments were made.

Another test used by several experimenters is the texture discrimination test. Subjects are given different textures of cloth, cotton, paper, sandpaper, wooden or metallic objects and then asked to compare objects based on coarseness or smoothness. It is very difficult to determine any type of numerical or translatable texture discrimination thresholds using these tests. Tests using sandpaper come closest to yielding consistent numerical data for analysis by using the sandpaper grade (grain/grit) as a basis of comparison between tested objects. Ekman (6) and Stevens and Harris (as found in James, 12) both determined that roughness judgments are a power function of the physical stimulus variable defined as the coefficient of friction or grit number of the sandpaper.

Sandpaper tests, besides not being rigorously numerical, have other drawbacks. Ekman (6) found that he had to use several identical sets of stimuli to avoid any noticeable change in the stimuli surface due to use. Poock (19), while searching for a test for the tactile sense, ran pilot experiments using emory paper and found, as had Ekman, that the skin and dirt from subjects' hands rubbed off too easily. He determined that the texture of the emory paper became noticeably different unless a different set of emory paper was prepared for each subject. Poock finally

settled on a test using as stimuli holes of different diameter drilled into a metal plate. Subjects were then directed to rank a set of four holes of various diameters from largest to smallest.

5. <u>Other Important Data Related to Tactual Tests</u>

Past tests of tactual discrimination reveal some other interesting results which should be considered when designing an experiment involving the sense of touch. For instance, it was determined that the size of random heptagons did not affect tactual discrimination of shape unless the size was varied within subjects; however, duration of exposure in the heptagon experiment was found to be significant (Lobb, 15). The subjects' body position is also important. Liddle and Foss (14) found that there is a difference in tactile perception of size when a subject's arm is extended when making comparisons and when the subject's arm is retracted when making comparisons.

Temperature was also found to be a significant factor in tactile sensitivity. Bowen (3), using the Mackworth "V" test, concluded that there exists a "fairly steady drop of tactile sensitivity with [water] temperature" (p. 23) among divers. Further discussion of Bowen's findings will be found in Chapter V.

III. PROCEDURE

A. TEST TYPE AND METHOD

A manual size discrimination test similar to that used by Poock (19) was selected for this experiment. The method used was the method of constant stimuli (as explained in Nunnally, 17).

B. STIMULI

The stimuli used were 3-inch squares of 1/4 inch-thick hard acrylic plastic with holes of varying dimensions drilled through the center. There were seven different hole diameters, starting with 29/32 inch and increasing in diameter by 1/32 inch to 35/32 inch.

C. TEST DESIGN

One complete test consisted of 98 comparisons to a standard hole dimension of one inch. Each size stimulus was presented to the subject fourteen times during the conduct of a test. The subject was presented the stimuli in a stack of seven at a time. Each stack contained one stimuli of each size hole dimension arranged in random order so that each size stimulus was presented as the top stimulus in the stack twice, second stimulus in the stack twice, ..., seventh stimulus in the stack twice. Four separate and randomly ordered tests were used. These tests can be seen in Appendix A, Tests. Data was taken as the number of correct/incorrect size discriminations for each hole dimension on each test. In those

instances where the hole dimension was the same size as the standard stimulus, the number of larger/smaller size determinations was recorded. A test "score" was determined to be the percentage of correct responses, deleting those stimuli that were the same size as the standard. In other words, score = (number of correct responses of stimulus other than those of one inch)/84.

D. TEST PROCEDURE

1. Subject Briefing

Each subject was told that the test was designed to determine the effects of submersion in water on tactile sensitivity. He was instructed to hold the standard stimulus in his non-dominant hand and the stimulus to be tested in his dominant hand for all testing. He was further instructed to hold the stimulus between his thumb and his index finger, or between his thumb and his middle finger, or between his thumb and both his index and middle fingers.

Subjects were told not to place the thumb or fingers completely inside the hole since preliminary testing had shown this method to be less accurate than feeling the surface where the hole was located. The subjects were allowed to move their finger and thumb in a rubbing type motion if they so desired. Since length of exposure is a significant factor, the subjects were instructed to pick up the tested stimulus, feel and compare the hole dimensions for three or four seconds, and then place the stimulus

in specially marked boxes. The standard and tested stimulus were not allowed to come into contact with each other and only "larger" or "smaller" size determinations were permitted.

2. <u>General</u>

Each subject was given one practice test to eliminate any confusion with the test and any learning effects. (Overall learning effects will be discussed in Section E.) Subjects then took one of the four standard tests while dressed in a complete wet suit with boots, but without gloves. For the practice test and the first test, the subjects were seated in the open air in front of a black box which contained the stimuli. The box served the purpose of preventing the subjects from making visual contact with the stimuli. The box contained two arm holes into which the subject placed his arms approximately three-quarters of the distance to his elbows. This first test was timed and would serve as the standard for comparison with the underwater tests. Air temperature was recorded during the administration of this test.

The second test was given immediately after the subject entered the water. The same black box used on the surface was used underwater. The box was placed in eight feet of water in a large swimming pool. The subjects used SCUBA air apparatus complete with mask and weight belt. During testing, the subjects removed their fins, stabilized their buoyancy by donning an extra weight belt, and knelt on the pool bottom in front of the black box.

After completion of the second test, the subjects removed the extra weight belt, donned fins, and remained in the pool performing free activity. A third test, using the same procedures, was administered after 30 minutes submersion time. After the third test, free activity was again permitted in the pool until the lapse of 60 minutes submersion time. A fourth test was then administered.

All tests were timed and the water temperature was measured during the conduct of the underwater tests at the test location.

The four standard tests were labelled A, B, C, and D respectively and each subject took Test A as his practice test. Each subject then took each of the four tests in random sequence during subsequent testing.

E. LEARNING EFFECTS

The test design which was used to evaluate the effect of underwater submersion on tactile sensitivity requires that each subject take four successive tests: one, before entering the water, and the other three at specified time intervals after submersion. To obtain accurate data, there can be no confounding of test results by learning effects. Therefore, extensive pre-testing was conducted to determine what learning effects are associated with the constant stimulus tests used for this experiment.

Thirteen subjects were given two successive tests and the data was analyzed using the ANOVA technique. The results of this analysis showed that there was a significant difference ($F = 4.36 > F_{.90} = 3.18$) between the two test scores; hence, a learning effect. Further testing with nine

subjects using ANOVA techniques where each subject took three successive tests revealed that there was no learning effect between the second and third tests ($F = 0.111 < F_{.90} = 3.46$). Testing with five subjects taking four successive tests showed further that there are no learning effects past the first test.

Based on this pre-testing analysis, each tested subject was required to take a practice test, Test A, before taking subsequent tests which would be numerically analyzed for submersion effects.

F. SUBJECTS

All ten subjects were male students at the Naval Postgraduate School, Monterey, California. The average subject age was 28.4 years (see Appendix B); all subjects were experienced SCUBA divers. Nine of the subjects were Navy officers and one was a Coast Guard officer. Only the Coast Guard officer was a professional diver.

IV. RESULTS

A. TESTING PARAMETERS

A detailed listing of the test parameters is located in Appendix B. The average air temperature taken during the open air test was 20.1°C. and varied $\pm$ 4°C. The average water temperature measured at the underwater testing site was 23.1°C. and varied $\pm$ 2.5°C. The data below shows the mean submersion time for each of the four tests.

Underwater Tests

	Immediate	30 minute	60 minute
Mean Submersion (Time in Minutes)	7.80	37.05	66.45

B. TEST SCORES

Test scores are listed in Appendix B. In order to determine if there were a statistically significant difference among the four test scores, the data was analyzed using the ANOVA (Analysis of Variance) technique. Since this technique involves many repititious calculations, the commonly used computer package BMD02V - Analysis of Variance for Factorial Design (Health Sciences Computing Facility, UCLA) was used. The results of this test show that there is no statistically significant difference among any of the tests; in other words, submersion of up to one hour and six minutes has no significant effect on test score. Below is a summary of the analysis of variance on test scores where test score = percentage of correct responses.

Source of Variation	Degrees of Freedom	Mean Squares	F Value
Between Subj	9	69.56944	3.30
Between Tests	3	14.62500	0.69 *
Residual	27	21.08795	----
Total	39	--------	----

* $F_{.90} = 2.30$, $F_{.95} = 2.96$

As a matter of interest, the data was analyzed using the same technique except that test score was determined as the number of incorrect responses. * Using this method of scoring, there is still no statistically significant difference among any of the tests. Below is a summary of the analysis of variance on test scores where test score = number of incorrect responses.

Source of Variation	Degrees of Freedom	Mean Squares	F Value
Between subjects	9	51.96939	3.96
Between tests	3	4.42498	0.34 **
Residual	27	13.11005	----
Total	39	--------	----

* Although this method has frequently been used in the past to score results of tests in tactile sensitivity, it limits the data derived by not accounting for the number of total responses.

** $F_{.90} = 2.30$, $F_{.95} = 2.96$

C. THRESHOLDS (DL'S) AND POINTS OF SUBJECTIVE EQUALITY (PSE'S)

When differential judgments are made, there is usually a zone of uncertainty within which the subjects are not able to judge accurately. This zone of uncertainty is frequently called the interval of uncertainty (IU) and ranges, in this study, from a stimulus size which is correctly judged as smaller seventy-five percent of the time to a stimulus size which is correctly judged as larger seventy-five percent of the time. The threshold or difference limen (DL) is that difference in stimulus size which is judged correctly seventy-five percent of the time; hence the threshold (DL) is one-half the size of the interval of uncertainty (IU).

A second term often found in studies examining differential judgment thresholds is the point of subjective equality (PSE). The point of subjective equality is that value of the comparison stimulus which is equally likely to be judged as smaller or larger.

The first method used to analyze the data for threshold and PSE determination is the linear interpolation process (Guilford, 9, p. 118-120). This process involved plotting percentage of larger (smaller) judgments against the stimulus size. These graphs are located in Appendix C. The calculations of the DL's and PSE's are also found in Appendix C. The data using the linear interpolation process is summarized below:

Tests	Interval of Uncertainty (IU) mm.	Threshold (DL) mm.	Point of Subject Equality (PSE) mm.
Open Air	1.915	0.96	25.1
Immediate	2.228	1.11	25.3
30 minute	2.096	1.05	25.2
60 minute	2.144	1.07	24.9

The second method used to analyze the data for threshold and PSE determination is the least-square normal approximation with unweighted observations technique discussed by Guilford (9, p. 125 - 129). Several different processes could have been used, such as Spearman's arithmetic-mean process and the summation method, but the test data in this case fits most closely the criteria for the use of the least-square technique (9, p. 134-135). The calculations of the DL's and the PSE's are located in Appendix C. The data using the least-square technique is summarized below :

Tests	Interval of Uncertainty (IU) mm.	Threshold (DL) mm.	Point of Subject Equality (PSE) mm.
Open Air	2.081	1.04	25.2
Immediate	2.148	1.07	25.4
30 minute	1.868	0.93	25.4
60 minute	1.855	0.93	25.1

V. CONCLUSIONS AND DISCUSSION

A. THE DIVING ENVIRONMENT

When a diver enters the underwater environment, which is eighty-two times more viscous than air, his performance is ordinarily expected to decrease. One researcher ventured the opinion that divers working underwater work only 15% as effectively as man on dry land (Mosby as quoted in Bowen, 3, p. 1). Vision underwater is restricted by the diver's mask, and depth and relative size perception are correspondingly disturbed. Other factors which could affect work ability and, thereby, tactile sensitivity are the diver's weightless state, the encumbrance of his protective wear and breathing apparatus, and, of course, the ever present hazard presented by the unnatural environment.

However, the most direct effect of working underwater on tactile sensitivity is undoubtedly temperature. Both Mackworth (16) and Bowen (3) have shown that cooling of the skin impairs tactile sensitivity, but past studies found that performance was only impaired when the hand skin temperature fell below 55° F. or body temperature below 69° F.

B. TEST SCORES

From the test score results shown in Chapter IV, it is clear that immediate and prolonged submersion in water of 23° C. (73.4° F.) had no effect on tactual size discrimination. This is similar to Hanna's findings

while working on the effects of total body immersion on weight discrimination . He concluded that "marked decrements in performance do not appear in the underwater sessions when compared to the land sessions as one might expect" (Hanna, 10, p. 5). In the present test, although the hand skin texture changed from dry, smooth, and taut on land to wet, wrinkled, and supple after prolonged underwater exposure, this change did not significantly alter the diver's tactual size discrimination.

C. THRESHOLD CORRELATION

Another measure of tactile sensitivity is the tactile threshold. The results of the present study, summarized in Chapter IV, reveal a threshold of approximately 1 mm. for all tests, land and underwater. Bowen (3, p. 22), however, found divers had thresholds of 5.3 - 5.6 mm. on dry land and 10.4 - 11.7 mm. in 72° F. water. Although the results of these two tests seem contradictory, Bowen's use of the Mackworth "V" test, a two-point limen-type test, may explain some of the discrepancy. Since accepted two-point thresholds in past works vary from 20 to 40 mm., it is difficult to compare Bowen's results with those of other researchers. Another difficulty is that Bowen's testing was done with the finger end pads while other researchers using two-point thresholds tested other parts of the body. However, it is still difficult to believe results that disclose significantly smaller tactile thresholds (8.4 - 8.6 mm.) in 62° F. water than those found in 72° F. water. Even though Bowen admits

that lower water temperatures have a degrading effect on tactile sensitivity, he does not offer an explanation for the above phenomenon.

Dolly Chan (4), using the "C"-ring test, found finger end pad thresholds of 2 - 4 mm. The "C"-ring test also yields a two-point threshold. As previously noted in the discussion, size discrimination threshold tests yield lower thresholds than do two-point limen tests; therefore, in comparison with Miss Chan's results, the thresholds of 1 mm. found as a result of the present test are as one might expect. Another possible explanation for the lower thresholds is Miss Chan's criterion for threshold determination as 80% correct responses as compared to the 75% used in this test.

Vierck and Jones (21) found size discrimination thresholds of 2 - 6 mm. on the forearm. It is quite natural to expect finger pads' thresholds to be smaller than this and, hence, the 1 mm. thresholds determined in this work again seem reasonable.

D. COMBINING CALCULATED RESULTS

There are interesting differences between the calculated DL's and PSE's when the linear interpolation method is used and when the normal approximation method is used. Each method has its drawbacks: the primary objection to the linear interpolation method is that it uses only two data points in computing the DL's and PSE's; the chief source of error in the normal approximation technique is that it is a curve fitting method and the data does not always closely fit a normal distribution. In fitting a normal approximation curve to the data results of this experiment, the

graphs in Appendix C show that the "percentage of responses to stimuli size" curves closely approximate the cumulative normal distribution curve shape (the phi-gamma hypothesis [Guilford, 9, p. 126]) for the first three tests, but that the curves for the 60-minute test deviate from the normal curve shape for the larger stimuli. With the drawbacks of both methods in mind, a reasonable way of combining the results obtained from these two analytic approaches would seem to be to average their values.

Averaging yields the following data:

	Averaged Data	
Tests	DL mm.	PSE mm.
Open Air	1.00	25.1
Immediate	1.09	25.4
30 minute	0.99	25.3
60 minute	1.00	25.0

The deviations of the DL's from the standard (Open Air) DL for both the 30 minute and 60 minute tests of 1% and 0% are quite insignificant by any criteria. The difference between the standard and the immediate test DL's can best be explained as adjustment to the underwater environment, especially since the PSE for the immediate test coincides with the standard hole dimension (1 inch or 25.4 mm.). The deviation of the PSE's from the

standard (Open Air) PSE for both the 30 minute and 60 minute tests of .8% and .4% are, again, by any criteria, insignificant.

E. FINAL CONCLUSION

The complete analysis of the results effectively show that submersion and length of submersion of up to one hour and six minutes in 23.1° C. water has no significant effect on tactile size discrimination within the limits investigated here. Furthermore, the results are consistent in themselves and with results of past research in the field of tactile sensitivity and size discrimination.

APPENDIX A

TESTS

Below are the four tests given to all subjects. Stimuli were presented to the subjects in a stack of seven at a time. Each of the four lettered tests consisted of fourteen stacks of stimuli. For easier reading, the hole dimensions have been keyed to numbers as indicated below:

Hole Dimension in Inches	Number Designation	Hole Dimension in Inches	Number Designation
29/32	1	33/32	5
30/32	2	34/32	6
31/32	3	35/32	7
32/32	4		

Test A

Stack Number	Order of Stimuli in Stack
1	1, 4, 5, 3, 6, 2, 7
2	2, 3, 6, 4, 5, 7, 1
3	4, 2, 1, 6, 7, 5, 3
4	3, 1, 7, 2, 4, 6, 5
5	7, 5, 3, 1, 2, 4, 6
6	6, 7, 2, 5, 1, 3, 4
7	5, 6, 4, 7, 3, 1, 2
8	6, 1, 4, 5, 3, 7, 2

Stack Number	Order of Stimuli in Stack
9	2, 6, 5, 3, 1, 4, 7
10	4, 7, 3, 1, 5, 2, 6
11	3, 5, 7, 4, 2, 6, 1
12	5, 3, 6, 2, 7, 1, 4
13	7, 2, 1, 6, 4, 5, 3
14	1, 4, 2, 7, 6, 3, 5

Test B

Stack Number	Order of Stimuli in Stack
1	6, 5, 3, 7, 2, 4, 1
2	4, 6, 5, 3, 1, 2, 7
3	5, 1, 6, 2, 3, 7, 4
4	1, 7, 4, 6, 5, 3, 2
5	7, 2, 1, 4, 6, 5, 3
6	3, 4, 2, 5, 7, 1, 6
7	2, 3, 7, 1, 4, 6, 5
8	4, 1, 2, 6, 3, 7, 5
9	1, 4, 5, 3, 2, 6, 7
10	2, 7, 4, 5, 1, 3, 6
11	6, 2, 1, 4, 7, 5, 3
12	3, 6, 7, 2, 5, 1, 4
13	5, 3, 6, 7, 4, 2, 1
14	7, 5, 3, 1, 6, 4, 2

Test C

Stack Number	Order of Stimuli in Stack
1	2, 7, 6, 5, 4, 1, 3
2	3, 4, 2, 7, 6, 5, 1
3	4, 3, 1, 2, 5, 7, 6
4	1, 5, 4, 6, 2, 3, 7
5	5, 6, 3, 1, 7, 2, 4
6	7, 1, 5, 4, 3, 6, 2
7	6, 2, 7, 3, 1, 4, 5
8	5, 3, 1, 6, 2, 4, 7
9	2, 1, 7, 3, 4, 6, 5
10	7, 5, 4, 2, 3, 1, 6
11	1, 4, 2, 5, 6, 7, 3
12	3, 2, 6, 1, 7, 5, 4
13	4, 6, 5, 7, 1, 3, 2
14	6, 7, 3, 4, 5, 2, 1

Test D

Stack Number	Order of Stimuli in Stack
1	4, 2, 7, 3, 6, 1, 5
2	5, 6, 4, 7, 1, 2, 3
3	7, 5, 6, 2, 4, 3, 1
4	2, 7, 1, 4, 3, 5, 6
5	6, 4, 3, 1, 5, 7, 2

Stack Number	Order of Stimuli in Stack
6	3, 1, 5, 6, 2, 4, 7
7	1, 3, 2, 5, 7, 6, 4
8	3, 6, 2, 5, 4, 7, 1
9	2, 1, 5, 6, 7, 4, 3
10	1, 7, 6, 4, 2, 3, 5
11	5, 3, 7, 2, 6, 1, 4
12	7, 5, 4, 3, 1, 2, 6
13	6, 4, 1, 7, 3, 5, 2
14	4, 2, 3, 1, 5, 6, 7

APPENDIX B

RAW DATA

Listed below are data accumulated on subjects and their related test parameters.

Subject Number	Subject Age	Air Temp °C	Water Temp °C	Duration of Test in Minutes			
				Test 1	Test 2	Test 3	Test 4
1	27	23.0	24.0	10	12	11	12
2	28	21.0	21.0	13	17	16	14
3	29	23.0	25.5	11	15	12	11
4	28	20.0	23.0	13	17	14	15
5	30	16.0	24.0	11	14	13	14
6	29	19.5	25.0	12	18	19	14
7	29	17.0	23.0	9	15	13	12
8	28	18.0	23.0	11	18	20	15
9	28	20.0	23.0	14	18	13	13
10	29	24.0	23.5	8	12	10	9
Sum	284	201.5	231.0	112	156	141	129
Average	28.4	20.1	23.1	11.2	15.6	14.1	12.9

The following are the test scores of the subjects. Test score is the percentage of correct discriminations to the nearest whole percent. Tests are labelled "Open Air," "Immediate," "30 min.," and "60 min." and refer to the test taken on land in the open air, the test taken

immediately upon subject's entry into the water, the test started after thirty minutes underwater, and the test started after one hour underwater respectively.

Subject Number	Test Score			
	Open Air	Immediate	30 min.	60 min.
1	80	76	83	89
2	98	89	87	92
3	82	83	87	91
4	80	73	83	81
5	80	71	80	81
6	85	82	76	77
7	81	82	81	87
8	87	90	83	82
9	77	91	87	79
10	89	85	86	92

The following four tables list the number of incorrect responses per stimulus for each of the four tests. Note that stimulus number four is the same size as the standard (comparative) stimulus and therefore responses of larger or smaller are neither correct nor incorrect. For this reason, the numbers under the column "4L" are the number of

larger responses for the number four stimuli and the numbers under the column "4S" are the number of smaller responses for the number four stimuli.

Open Air Wrong Responses

Subject Number	Stimulus Number 1	2	3	5	6	7	4L	4S
1	1	6	8	2	0	0	12	2
2	0	0	1	0	1	0	6	8
3	0	4	5	5	1	0	8	6
4	1	0	2	5	5	4	8	6
5	3	3	6	6	1	0	7	7
6	1	5	7	0	0	0	13	1
7	0	0	2	4	6	4	8	6
8	0	1	6	3	0	1	7	7
9	3	7	9	0	0	0	13	1
10	0	0	0	7	1	1	4	10
Totals	9	26	46	32	15	10	86	54
% Responses, Larger	6.4	18.6	32.9	77.2	89.3	92.9	61.4	--
% Responses, Smaller	93.6	81.4	67.1	22.8	10.7	7.1	--	38.6

Immediate Wrong Responses

Subject Number	Stimulus Number 1	2	3	5	6	7	4L	4S
1	0	11	7	1	1	0	11	3
2	0	1	3	3	2	0	8	6
3	1	1	3	7	1	1	4	10
4	0	0	1	11	5	6	2	12
5	3	5	10	3	2	1	9	5
6	2	4	10	1	0	0	14	0
7	1	0	0	9	3	2	7	7
8	0	0	1	5	2	0	3	11
9	1	2	5	0	0	0	10	4
10	0	1	1	7	3	1	5	9
Totals	8	25	41	47	19	11	73	67
% Responses, Larger	5.7	17.9	29.3	66.3	86.4	92.1	52.1	--
% Responses, Smaller	90.3	82.1	70.7	33.6	13.6	7.9	--	47.9

30 Min. Wrong Responses

Subject Number	Stimulus Number 1	2	3	5	6	7	4L	4S
1	0	4	9	1	0	0	13	1
2	1	0	0	6	3	1	8	6
3	0	2	6	2	0	1	10	4
4	0	0	0	6	5	3	7	7
5	2	5	4	3	2	1	9	5
6	1	8	11	0	0	0	13	1
7	1	1	3	7	2	2	5	9
8	0	0	0	9	4	1	5	9
9	0	2	7	2	0	0	10	4
10	0	0	0	8	3	1	4	10
Total	5	22	40	44	19	10	84	56
% Responses, Larger	3.6	15.7	28.6	68.6	86.4	92.9	60	--
% Responses, Smaller	96.4	84.3	71.4	31.4	13.6	7.1	--	40

60 Min. Wrong Responses

Subject Number	Stimulus Number 1	2	3	5	6	7	4L	4S
1	2	3	12	0	0	0	13	1
2	0	0	1	5	1	0	8	6
3	0	1	5	1	1	0	9	5
4	0	0	2	9	3	2	5	9
5	2	2	7	4	0	1	9	5
6	2	7	10	0	0	0	14	0
7	0	1	4	5	0	1	9	5
8	1	0	4	6	2	2	11	3
9	1	7	7	3	0	0	12	2
10	0	0	0	7	0	0	5	9
Total	8	21	52	40	7	6	95	45
% Responses, Larger	5.7	15.0	37.2	71.4	95.0	95.7	67.9	--
% Responses, Smaller	94.3	85.0	62.8	28.6	5.0	4.3	--	32.1

APPENDIX C

LINEAR CALCULATIONS AND GRAPHS

Listed below are definitions of the terms used in this appendix.

PSE = point of subjective equality, value of the comparison stimulus which is equally likely to be judged as smaller or larger

IU = interval of uncertainty

DL = difference limen, differential threshold

L_h = higher threshold

L_l = lower threshold

S_a = stimulus immediately above upper threshold

S_b = stimulus immediately below upper threshold

P_a = % larger judgments for stimulus immediately above upper threshold

P_b = % larger judgments for stimulus immediately below upper threshold

C = proportion of judgments which define upper threshold criterion, 75%

T_a = stimulus immediately above lower threshold

T_b = stimulus immediately below lower threshold

q_a = % larger judgments for stimulus immediately above lower threshold

q_b = % larger judgments for stimulus immediately below lower threshold

C' = proportion of judgments which define lower threshold criterion, 25%

M_a = stimulus above intersection *

M_b = stimulus below intersection *

r_a = % judgments for stimulus immediately above intersection *

r_b = % judgments for stimulus immediately below intersection *

C'' = proportion of judgments which define median, 50%

Formulas are as follows:

$$L_h = S_b + \frac{(S_a - S_b)(C - P_b)}{(p_a - p_b)}$$

$$PSE = M_a + \frac{(M_a + M_b)(C'' - r_b)}{(r_a - r_b)}$$

$$L_1 = T_b + \frac{(T_a - T_b)(C' - q_b)}{(q_a - q_b)}$$

$$IU = L_h - L_1$$

$$\text{Mean DL} = IU/2$$

---

* Intersection of "percentage of judgments larger" graph with "percentage of judgments smaller" graph. See graphs this appendix.

Open Air Calculations:

$$L_h = \frac{32}{32} + \frac{(33/32 - 32/32)\ (75 - 61.4)}{(77.2 - 61.4)} = 1.0269 \text{ in.}$$

$$L_1 = \frac{30}{32} + \frac{(31/32 - 30/32)\ (25.0 - 18.6)}{(32.9 - 18.6)} = 0.9515 \text{ in.}$$

IU = 1.0269 - 0.9515 = 0.0754 in.

= 1.92 mm.

Mean DL = 0.96 mm.

$$PSE = \frac{31}{32} + \frac{(32/32 - 31/32)\ (50.0 - 32.9)}{(61.4 - 32.9)} = 0.9875 \text{ in.}$$

= 25.08 mm.

Immediate Calculations:

$$L_h = \frac{32}{32} + \frac{(34/32 - 33/32)\ (75.0 - 66.3)}{(86.4 - 66.3)} = 1.0447 \text{ in.}$$

$$L_1 = \frac{30}{32} + \frac{(31/32 - 30/32)\ (25.0 - 17.9)}{(29.3 - 17.9)} = 0.9570 \text{ in.}$$

IU = 1.0447 - 0.9570 = .0877 in.

= 2.23 mm.

Mean DL = 1.11 mm.

$$PSE = \frac{31}{32} + \frac{(32/32 - 31/32)\ (50.0 - 29.3)}{(52.1 - 29.3)} = 0.9971 \text{ in.}$$

= 25.32 mm.

30 Minute Calculations:

$$L_h = \frac{33}{32} + \frac{(34/32 - 33/32)(75.0 - 68.6)}{(86.4 - 68.6)} = 1.0425 \text{ in.}$$

$$L_1 = \frac{30}{32} + \frac{(31/32 - 30/32)(25.0 - 15.7)}{(28.6 - 15.7)} = 0.9600 \text{ in.}$$

IU = 1.0425 - 0.9600 = .0825 in.

= 2.10 mm.

Mean DL= 1.05 mm.

$$PSE = \frac{31}{32} + \frac{(32/32 - 31/32)(50.0 - 28.6)}{(60.0 - 28.6)} = 0.9900 \text{ in.}$$

= 25.15 mm.

60 Minute Calculations:

$$L_h = \frac{33}{32} + \frac{(34/32 - 33/32)(75.0 - 71.4)}{(95.0 - 71.4)} = 1.0360 \text{ in.}$$

$$L_1 = \frac{30}{32} + \frac{(31/32 - 30/32)(25.0 - 15.0)}{(37.2 - 15.0)} = 0.9516 \text{ in.}$$

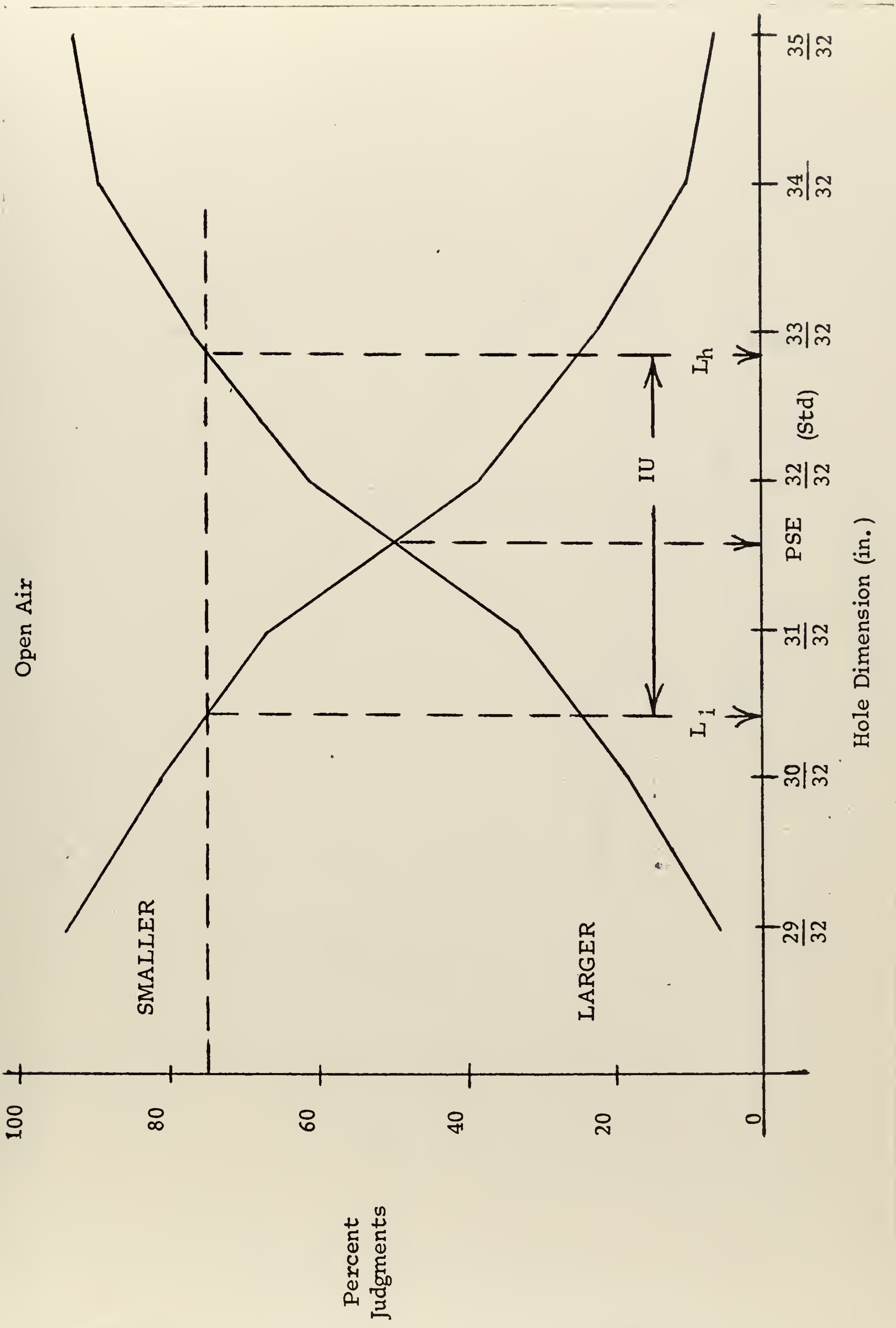
IU = 1.0360 - 0.9516 = 0.0844 in.

= 2.14 mm.

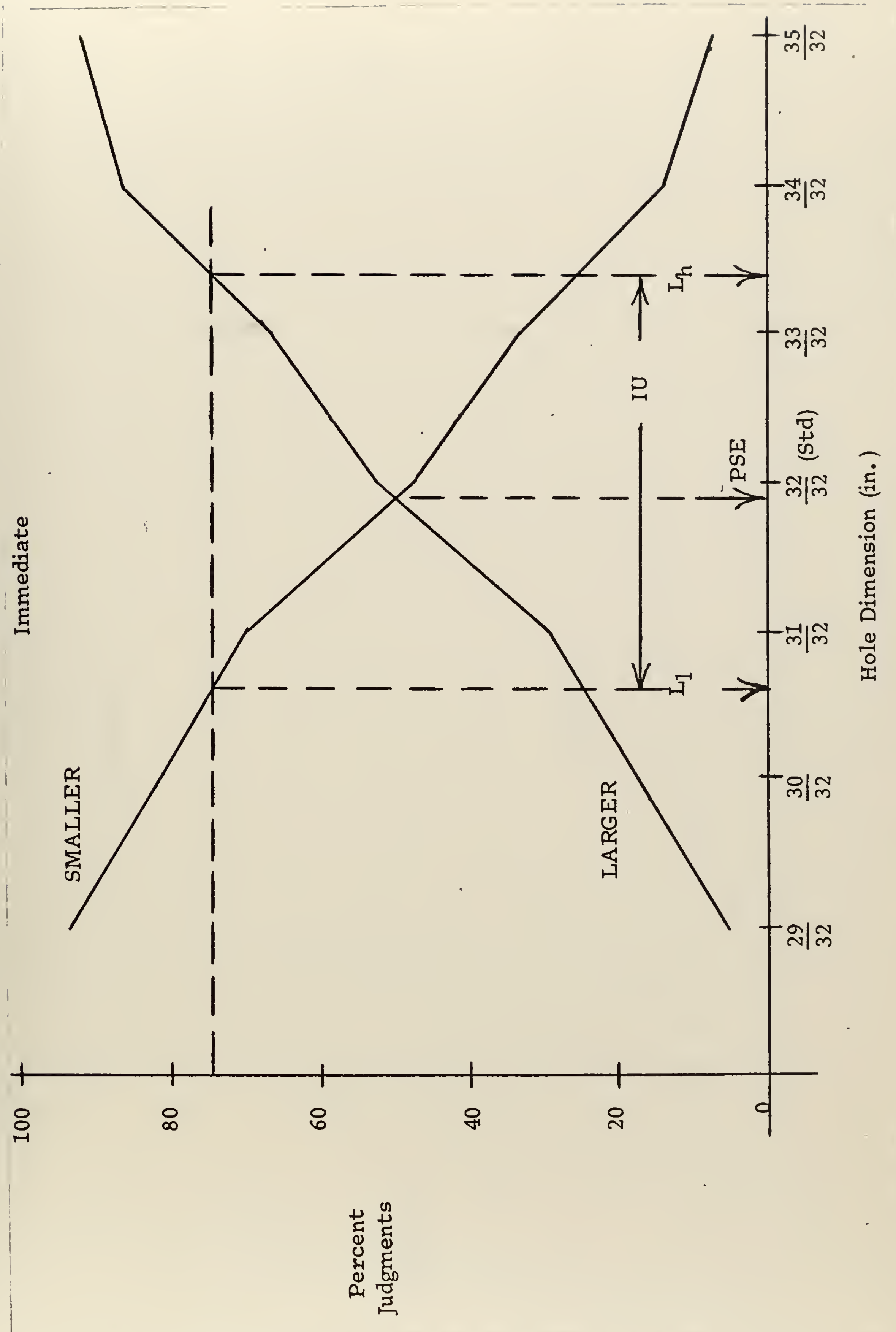
Mean DL = 1.07 mm.

$$PSE = \frac{31}{32} + \frac{(32/32 - 31/32)(50.0 - 37.2)}{(67.9 - 37.2)} = 0.9818 \text{ in.}$$

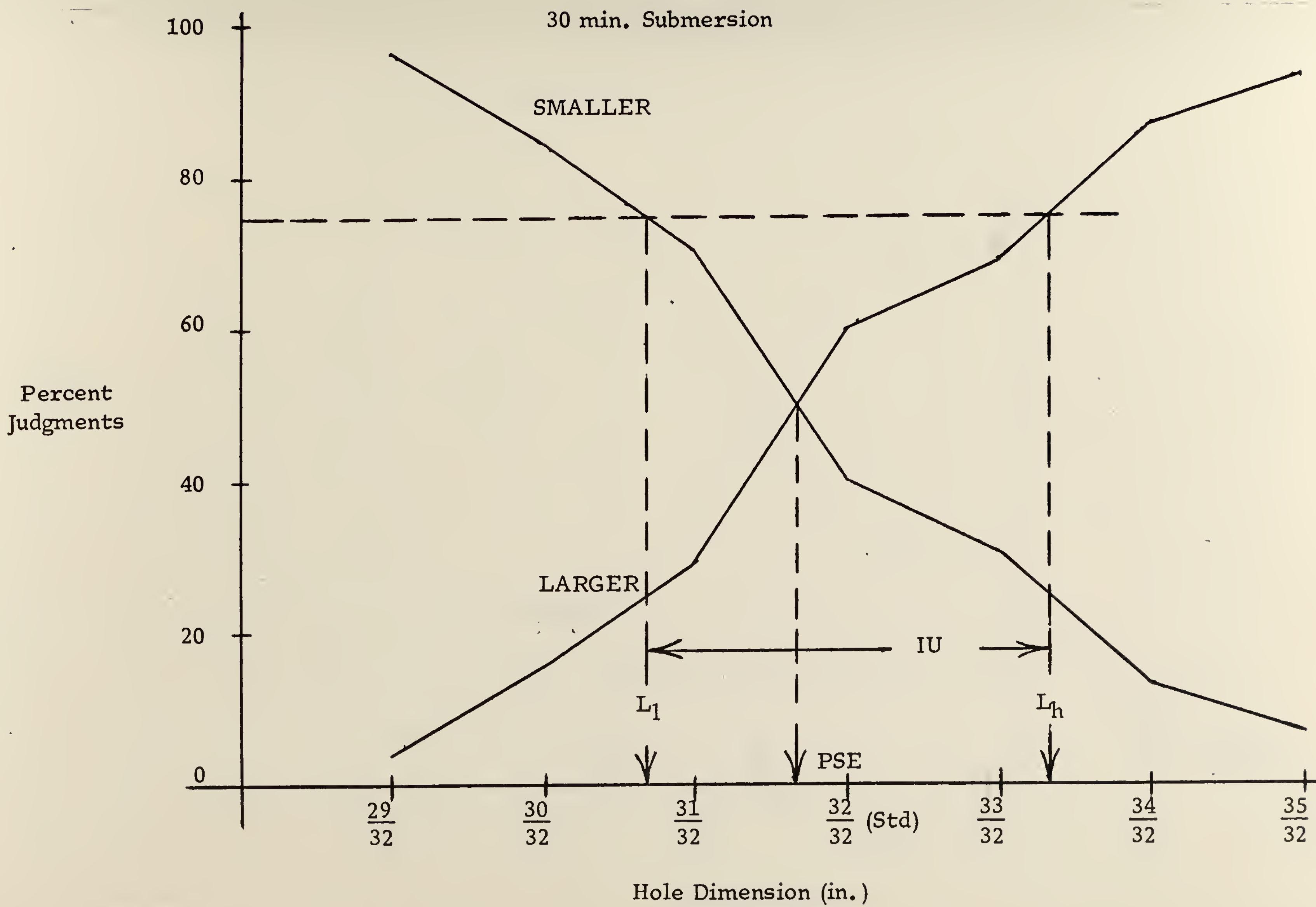
$$= 24.94 \text{ mm.}$$

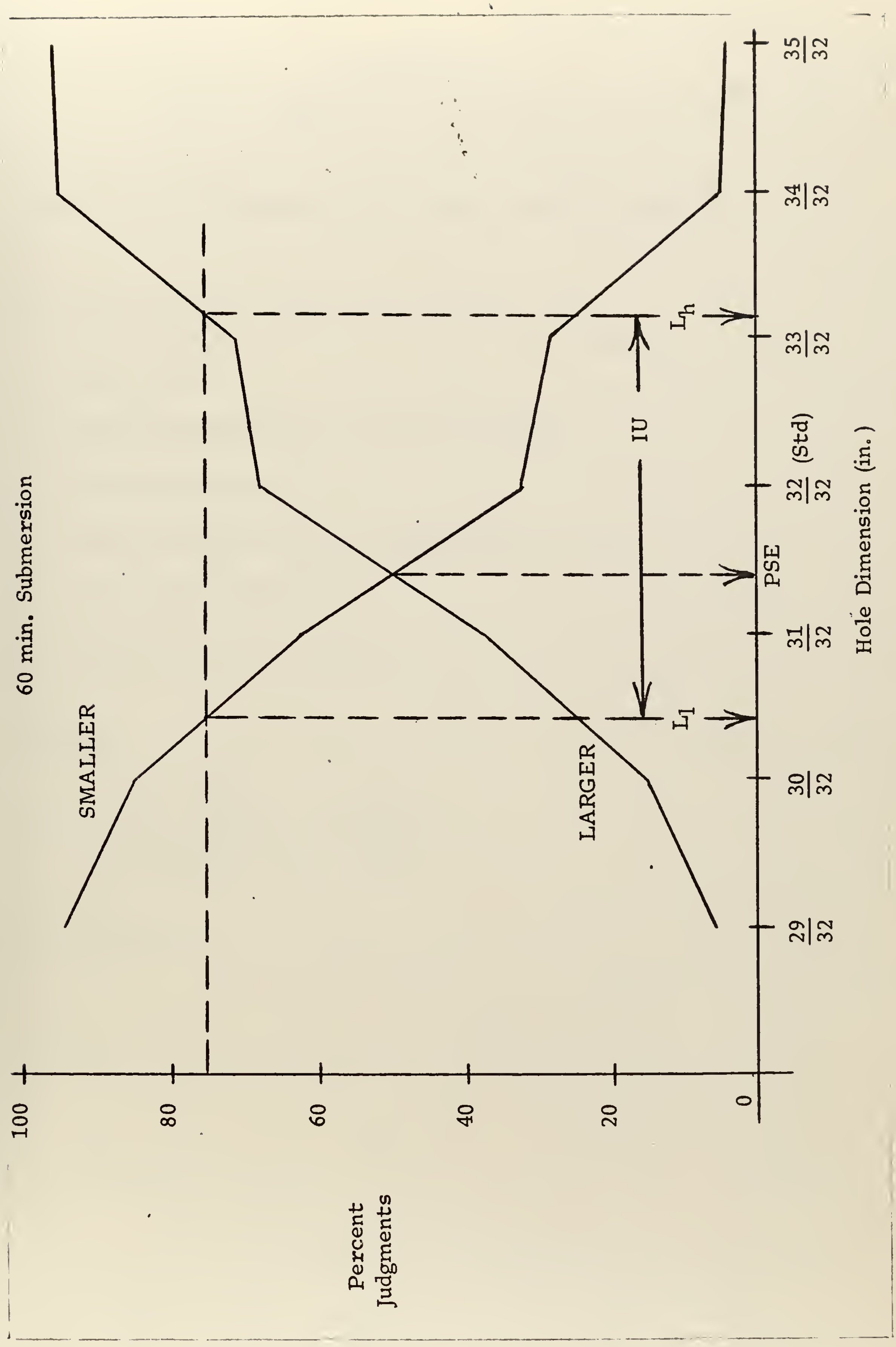


Open Air
SMALLER
LARGER
Percent Judgments
100
80
60
40
20
0
29/32
30/32
31/32
32/32 (Std)
33/32
34/32
35/32
L_l
PSE
IU
L_h
Hole Dimension (in.)



Immediate
SMALLER
LARGER
Percent
Judgments
100
80
60
40
20
0
$\frac{29}{32}$
$\frac{30}{32}$
$\frac{31}{32}$
$\frac{32}{32}$ (Std)
$\frac{33}{32}$
$\frac{34}{32}$
$\frac{35}{32}$
Hole Dimension (in.)
PSE
IU
L_l
L_h


30 min. Submersion
Percent Judgments
100
80
60
40
20
0
SMALLER
LARGER
IU
L_l
L_h
PSE
$\frac{29}{32}$
$\frac{30}{32}$
$\frac{31}{32}$
$\frac{32}{32}$ (Std)
$\frac{33}{32}$
$\frac{34}{32}$
$\frac{35}{32}$
Hole Dimension (in.)


60 min. Submersion
SMALLER
LARGER
Percent Judgments
100
80
60
40
20
0
29/32
30/32
31/32
32/32 (Std)
33/32
34/32
35/32
L_l
PSE
IU
L_h
Hole Dimension (in.)

APPENDIX D

NORMAL APPROXIMATION CALCULATIONS

Listed below are definitions of the terms used in this appendix:

M' = guessed mean, in this case the standard 1-inch

L = limen mean

i = stimulus value interval (constant), 1/32 inch

S' = coded stimulus values

z = standard normal value of x where % larger = F(x)

d = limen standard deviation

n = number of sizes of stimuli, 7

Formulas:

$$L = M' - \left(\frac{\sum S'^2 \sum z}{n \sum S' z} \right) i \qquad d = \frac{\sum S'^2}{\sum S' z}$$

$$IU = 1.35d$$

Open Air Calculations:

Stimulus Number	% Judgments Larger	S'	Z	S'^2	$S'Z$
7	92.9	+3	+1.47	+9	+4.41
6	89.3	+2	+1.24	+4	+2.48
5	77.2	+1	+0.75	+1	+0.75
4	61.4	0	+0.29	0	0
3	32.9	-1	-0.44	+1	+0.44
2	18.6	-2	-0.89	+4	+1.78
1	6.4	-3	-1.52	+9	+4.56
Summation			+0.90	28	14.42

$$L = 1 - \frac{(28)(.9)}{(7)(14.42)}\left(\frac{1}{32}\right) = .99220 \text{ in.}$$

$$= 25.202 \text{ mm.}$$

$$d = \frac{28}{14.42}\left(\frac{1}{32}\right) = 0.06068 \text{ in.}$$

IU = 0.0819 in.

= 2.081 mm.

DL = 1.040 mm.

Immediate Calculations:

Stimulus Number	% Judgments Larger	S'	Z	S'^2	$S'Z$
7	92.1	+3	+1.41	+9	+4.23
6	86.4	+2	+1.10	+4	+2.20
5	66.3	+1	+0.42	+1	+0.42
4	52.1	0	+0.05	0	0
3	29.3	-1	-0.54	+1	+0.54
2	17.9	-2	-0.92	+4	+1.84
1	5.7	-3	-1.58	+9	+4.74
Summation			-0.06	28	13.97

$$L = 1 - \frac{(28)\quad(-.06)}{(7)\quad(13.97)}\left(\frac{1}{32}\right) = 1.00054 \text{ in.}$$

$$= 25.414 \text{ mm.}$$

$$d = \frac{28}{13.97}\left(\frac{1}{32}\right) = .06263 \text{ in.}$$

$$IU = 0.0846 \text{ in.}$$

$$= 2.148 \text{ mm.}$$

DL = 1.074 mm.

30 minute Calculations:

Stimulus Number	% Judgments Larger	S'	Z	S'^2	$S'Z$
7	92.9	+3	+1.47	+9	+4.41
6	86.4	+2	+1.10	+4	+2.20
5	68.6	+1	+0.49	+1	+0.49
4	60.0	0	+0.25	0	0
3	28.6	-1	-0.82	+1	+0.82
2	15.7	-2	-1.37	+4	+2.74
1	3.6	-3	-1.80	+9	+5.40
Summation			-0.68	28	16.06

$$L = 1 - \frac{(28)\ \ (-0.68)}{(7)\ \ (16.06)}\left(\frac{1}{32}\right) = 1.00529 \text{ in.}$$

$= 25.414$ mm.

$$d = \frac{28}{16.06}\left(\frac{1}{32}\right) = 0.05448 \text{ in.}$$

IU = 0.07355 in.

= 1.868 mm.

DL = 0.934 mm.

60 minute Calculations:

Stimulus Number	% Judgments Larger	S'	Z	S'^2	$S'Z$
7	95.7	+3	+1.72	+9	+5.16
6	95.0	+2	+1.64	+4	+3.29
5	71.4	+1	+0.57	+1	+0.57
4	67.9	0	+0.47	0	0
3	37.2	-1	-0.33	+1	+0.33
2	15.0	-2	-1.04	+4	+2.08
1	5.7	-3	-1.58	+9	+4.74
Summation			+1.45	28	16.17

$$L = 1 - \frac{(28)\ (1.45)}{(7)\ (16.17)}\left(\frac{1}{32}\right) = 0.98879 \text{ in.}$$

$$= 25.1153 \text{ mm.}$$

$$d = \frac{28}{16.17}\left(\frac{1}{32}\right) = 0.05411 \text{ in.}$$

IU = 0.07305 in.

= 1.856 mm.

DL = 0.9277 mm.

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13. ABSTRACT

This thesis examines the effects of underwater submersion and prolonged underwater submersion on a diver's tactile sensitivity. The method of constant stimulus is used to determine size discrimination thresholds. The stimuli used are squares of hard acrylic plastic into which holes of varying diameters have been drilled.

Four tests were administered to each subject. One test was administered on dry land in the open air and served as the standard. The other three tests were administered underwater at various time intervals.

The conclusion drawn from this research is that a diver's tactile sensitivity as measured by his ability to make size discriminations is not affected by underwater submersion or even prolonged underwater submersion of sixty-six minutes. Furthermore, the thresholds of approximately one millimeter, determined in this thesis, are consistent with the findings of past research in this field.

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Cutaneous Sensitivity						
Diver Tactile Sensitivity						
Sense of Touch						
Human Performance						
Diving						
Touch						

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